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Simulation research on human evacuation in subway with a single-point fire scenario

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Abstract

FDS+EVAC code is used to simulate the personnel evacuation in Nanjing Yangtze River Tunnel. When fire occurs in the middle of train. The train can choose to stop immediately in the tunnel or keep moving to the nearest station to evacuate passengers on condition of fire accident. The influence of emergency measures on evacuation was also discussed. The regularity of smoke flow, concentration of CO and CO_2 and temperature distribution were calculated. Two kinds of evacuation models were proposed and validated. If the train breaks down because of fire and stops in the tunnel, the available evacuation program is fail to ensure passengers' safety.

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Keywords: subway fire; evacuation;simulation; FDS; EVAC

1. Introduction

With the development of society, the role which subway train plays in urban transit system has been more and more important. Plenty of subway lines has been put into use in the major cities. In addition, the construction of subway transit system has been improved. Drawbacks of subway system like complicated structure, big personnel concentration, high fire load and few evacuation exits have been revealed, while it has advantages of large carrying capacity, high speed, little influence by weather and perfect timing control. Due to the special underground structure of subway train, the temperature of subway station and tunnel will increase rapidly and high concentration of smoke

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will gather when carriage catches fire. Rapid evacuation will be difficult because of the limited underground space and connection tunnel. Unfortunately, it will cause serious accidents of many casualties.

The current study of subway evacuation through computer simulations focuses on the smoke diffusion in the tunnel and carriages. Also, the flow of smoke in subway station, tunnel and carriages during the fire will be studied. The space of safe evacuation will be ensured by setting certain smoke layer height and the time will be determined by observing the time of smoke diffusion. However, there’s no fire and evacuation happening in the same time. Only analyze the motion of smoke in the fire and human motion parameters in normal conditions without considering the change of human thinking and behavior patterns in emergency will make the setting conditions for safe evacuation deviates from reality. Therefore, it will be more objective and comprehensive through simulating the fire and evacuation simultaneously by FDS+EVAC and more reliable theories for certain contingency and evacuation plans will be provided.

2. Model

The simulation study is based on Nanjing Yangtze River Tunnel. The tunnel is designed with single hole and double line, with the diameter of 11.3 mand the length of 3600m. There is a distance of 2700m under the river and a emergence exit every 600m. The model is illustrated in Fig. 1.

a b

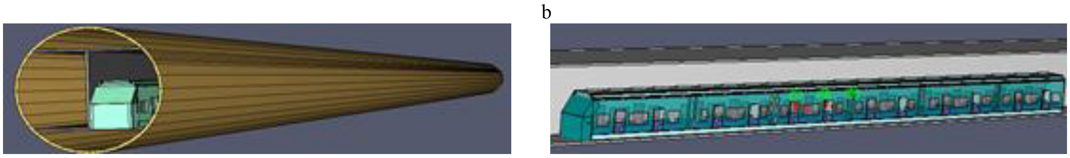

Fig. 1. (a) tunnel model; (b) train model.

The train is composed of 6 A type carriages, car length 22m, width 3M, high 3.8m， the distance between bottom surface of carriage and track is 1.1m, and the height of the carriage is 2.1m, with its cross sectional area of 11.4 m^2.The simulation consists of a 600m tunnel between two emergency exits. The mesh of the fire simulation was setted as $0.5\times0.2\times0.2$ and the evacuation mesh was $0.2\times0.2\times2$. Besides, the fire source is located in the middle of the train and the heat flux is 4MW. The fuel is petrol and the heat release rate reach its peak value at 206s. The number of passengers is 1000, 53.5% of the full load capacity.

3. Scheme

There is a emergence exit every 600m. Along the ordinary route, while the subway catch fire, the train will arrive at the station under the special condition. Besides, the firewill be put out after the passengers are evacuated. In this simulation, the length is 245% increased, compared to the average space (1470m) between stations. Hence, there are two situations compared as pull-in evacuating and local evacuating. For local evacuating, the fire scene is set the worst. The middle of the train is 300m away from the exit. The distance between passengers and emergence exit and the time are the longest. And it requests the hardest safe evacuation condition. Therefore, the simulation is based on this situation.

4. Simulation

4.1. Simulation stops evacuation

The subway comes into the station in the form of uniform deceleration motion and the emergency braking distance is 200m, moreover, its total distance is 1800m with corresponding time of 120s. The crowed evacuation time in a train full of passengers needs 0.61min, thereby 20s is completely enough for the evacuation of 55% of passengers. As a result, this paper's main concern is the period (i.e. 120s) between the discovery of fire and the subway pulling into the station.

According to the simulation results, the temperature distributions of a carriage at 60s and 120s are presented in Fig. 2.

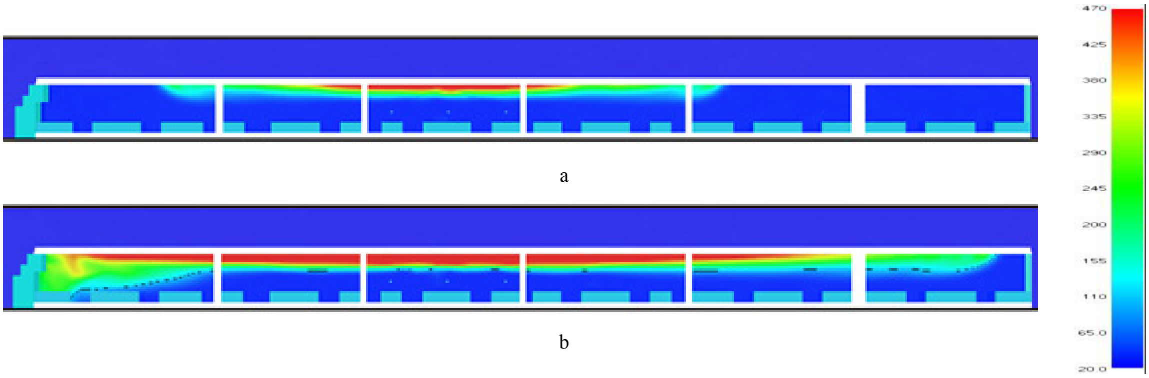

Fig. 2. (a) temperature distribution: 60s; (b) temperature distribution: 120s.

As can be seen from Fig. 2(a), high temperature smoke is aggregated in the roof of the carriage in the early phase of a fire, this is because the high temperature smoke continuously created by fire source are affected by buoyancy. So gases in the roof spread along the two ends of the carriage under the effect of center pressure and gas frontier is cooled with its temperature decreasing. At this time, although the air conditioning system reduces the temperature in the carriage, it blows part of the smoke to the passengers and increases the risks of suffocation and poisoning.

As can be seen from Fig. 2(b), smoke layer begins to drop along the carriage wall as the subway pulls in the station at 120s and the first carriage is full of smoke. Besides, in the development of subway fire, smoke in the low space near fire source has both lower temperature and concentration. This indicates that in a closed space (like carriage, etc.), the position far from fire source will be full of smoke first whereas the position close to fire source is relatively safe. In addition, due to evading psychology, passengers waiting for rescue will be far from fire source and gather at the two sides of the carriage, which can result in the increases of the casualties.

Fig. 3 presents the distribution of CO_2 concentration in a carriage at 60s and 120s.

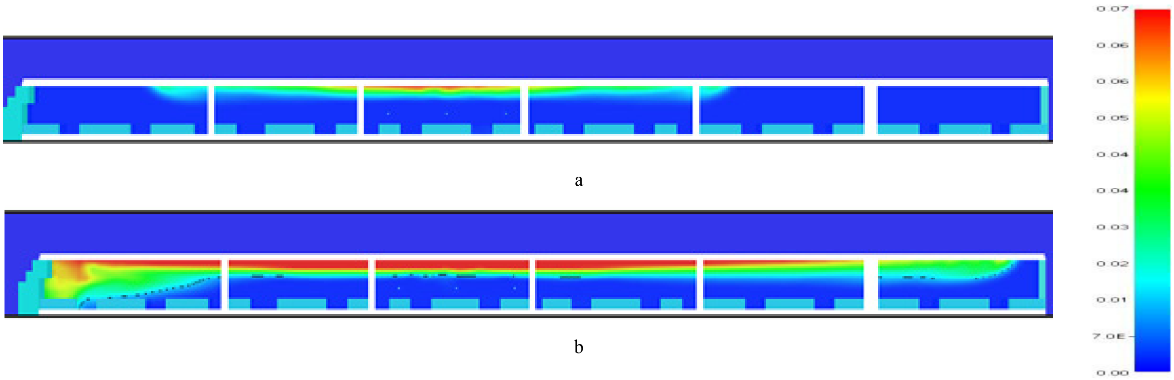

Fig. 3. CO_2 distribution in the car: (a) 60s; (b) 120s.

According to Fig. 3, the roof of carriage has higher CO_2 concentration at 60s after a fire due to the high temperature smoke flow. The concentration position of CO_2 is relatively high and its average concentration is lower than the lowest concentration which will produce harm, hence CO_2 concentration is presently safe. The CO_2 and temperature distributions are consistent to a high degree compared to Fig. 2(a), which indicates that although CO_2 is heavier than air and will settle down in general situation, the motion laws of CO_2 concentration and high temperature smoke are consistent in the carriage.

At 120s, the diffusion path of CO_2 is still accordance with the high temperature smoke flow. AfterCO_2arriving at the two sides of carriage, the first carriage is gradually full of it and the gas concentration is basically uniform in the carriage. Moreover, at this moment the diffusion mode is different from that of 120s, that is smoke close to roof forms a high-concentration gas layer, which moves forward the two sides. After CO_2 filling the carriage, the smoke spread from the two sides to middle as well as from top to down until the whole subway is filled with CO_2. At 120s, the subway has stopped and the door is opened to for evacuation. Besides, CO_2 gas layer has not fallen into the height where people locate, thereby CO_2 will not produce harm to people when the subway is running.

Fig. 4 presents the distribution of CO volume concentration in a carriage.

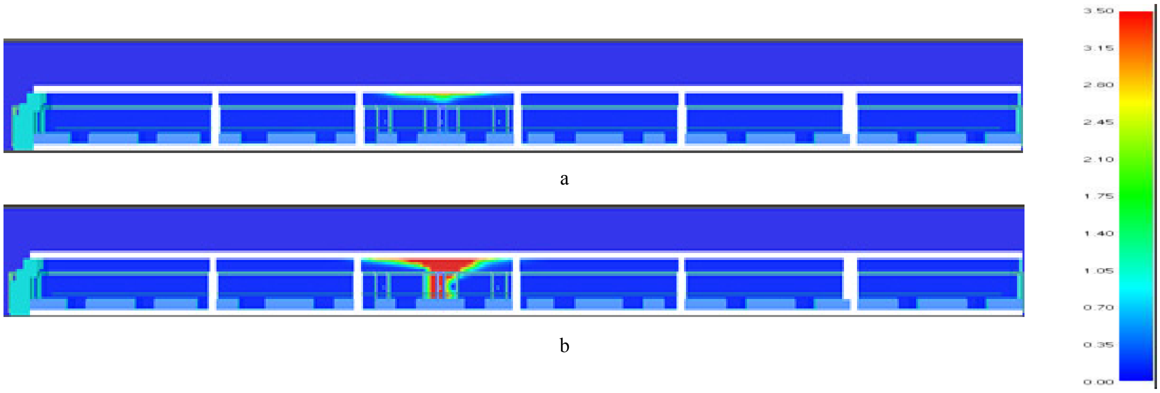

Fig. 4. CO distribution in the car: (a) 60s; (b) 120s.

At 60s, the CO content is awfully low in the carriage and distributed above fire source, which will not pose a danger to passengers.

At 120s, the distribution of CO is similar to that of 90s without speedy diffusion, but the intensity of fire source does not reach the peak value and is still in the rising phase, which illustrates CO concentration remaining unchanged is deriving from fire source obtaining an adequate supply of fresh air.

The distribution of CO_2 concentration can be observed through the slice record and the CO_2 concentration along the axial plane of subway can not lead to cases of passenger poisoning. However, three monitors at the height of 1m, 1.5m and 2m are set up because of people's sensibility of CO, which are used to monitor the distribution of CO_2 concentration. The data of three monitors is presented in Fig. 5.

As can be seen from Fig. 5, from the subway catching fire to the evacuation of passengers, the CO concentration has not changed much at 1m. In 120s, the CO concentration is low at 1m, which is far below the hold value of causing harm to human bodies. The peak value of CO ($0.5mg/m^3$) appears at about 140s and an exposure of 1–2h can result in dizziness and vomit, however, under this condition people are stay for about 20s in reality, which will not cause any harm.

According to the green line in Figure 5, in 120s, the CO concentration has a fluctuation at 1.5m and its peak value ($0.004mg/m^3$) shows up at 120s, which is far below the hold value of causing harm to human bodies. However, in 140s, the CO concentration has a significant fluctuation at 1.5m but it is far below CO concentration at 1m, which indicates smoke continuously spreads during the ascent of CO. And meanwhile it is added to the combustion reaction decreasing the CO content as a whole.According to Fig. 5, the measured values of CO concentration at 2m are extremely unstable and its peak value ($0.02mg/m^3$) can not cause harm to human bodies. This is because this height is close to the roof of passenger compartment where the flow of smoke is fast and complex.

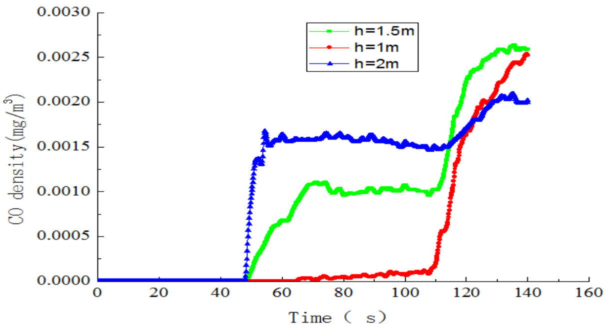

Fig. 5. The variation of CO concentration in different heights.

Synthesizing the CO concentrations along slice record in different time with the monitoring data of CO at three heights, the fact that CO concentration will not cause harm to people is determined. Besides, after the analysis of passenger's evacuation when subway pulls in the station, temperature, CO and CO_2 will not cause the sequence of larger-scale casualties. But there is a possible suffocation hazard while the carriage is full of smoke at about 120s. In general, the hazard of the evacuation program for subway pulling in the station is controllable and low-level with the low likelihood of causing severe harm to people.

4.2. *Simulation of situ evacuation*

When situ evacuation occurs, the emergency exits in the front and rear side of subway train are ideal locations to evacuate.

As is shown in Fig. 6, the distribution and changes of the volume concentration of CO in the carriage will be analyzed in the following .

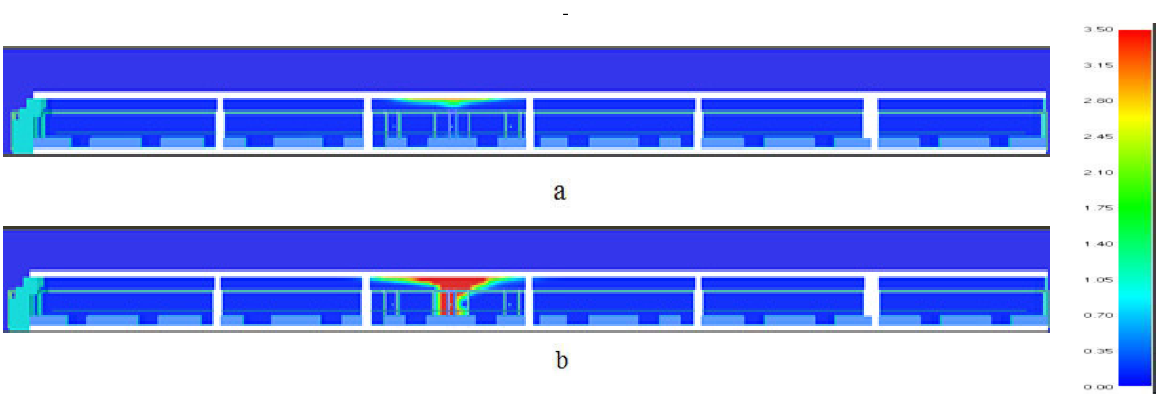

Fig. 6. CO distribution in the car: (a) 60s; (b) 120s.

Due to Fig. 6, the content of CO is low inside the carriage and the distribution area is concentrated on the top of fire source in 60s, which will not cause damage to the passengers.

In 120s, the distribution of CO does not spread rapidly with a higher concentration than 60s due to Fig. 6(b). However, the fire source does not reach the peak value yet and is still in the rising phase, which illustrates fuel inside the carriage still has a perfect combustion and the concentration of CO will not change greatly. Here we can come to the conclusion that the concentration and distribution of CO in the carriage will not cause damage to the passengers from the start of fire to the basic end of evacuation. Considering of the small distribution and low concentration of CO and the small variation of data in monitoring point, we will not analyze the data of CO.

Then, as is shown in Fig. 7, the change of distribution and concentration of CO_2 will be analyzed.

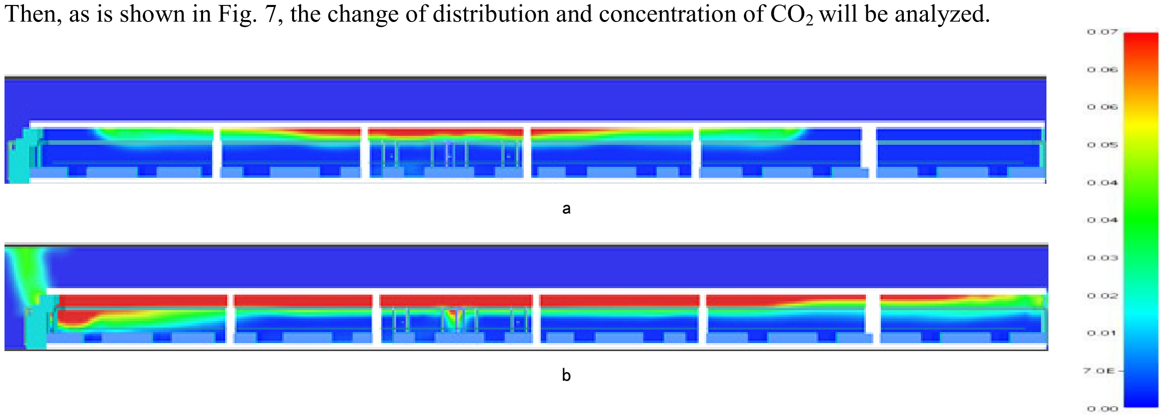

Fig. 7. CO_2 distribution in the car: (a) 60s; (b) 120s.

Due to Fig. 7(a), content of CO_2 on the roof of carriage is high with the high temperature smoke flowing after 60s. The enrichment area of CO_2 still has a distance from the passengers, and the average concentration is far lower than the concentration to cause damage. Therefore, CO_2 will not cause damage to the passengers.

Due to Fig. 7(b) the emergency exit on both ends of the carriage will open in 120s, leading to air convection inside and outside the carriage and high spreading speed of smoke. Compared with the situation in which the carriage is airtight in Fig. 3(b), the high temperature part of smoke has already reached the front side of the carriage in 120s, while in Fig. 3(b) the frontier of smoke has just fulfilled part of the first carriage, which comes to conclusion that the evacuating speed in situ evacuation is faster than the carriage is airtight. The effect of evacuation will be influenced by the smoke filled environment ,because the evacuation has just completed 55.6% ,while the whole evacuation time is 226s during the phase. Situation like crowding, stampede and fighting behavior caused by panic passengers can't be simulated, so the result of simulation is already the ideal evacuation.

The distribution of temperature in the car is as Fig. 8.

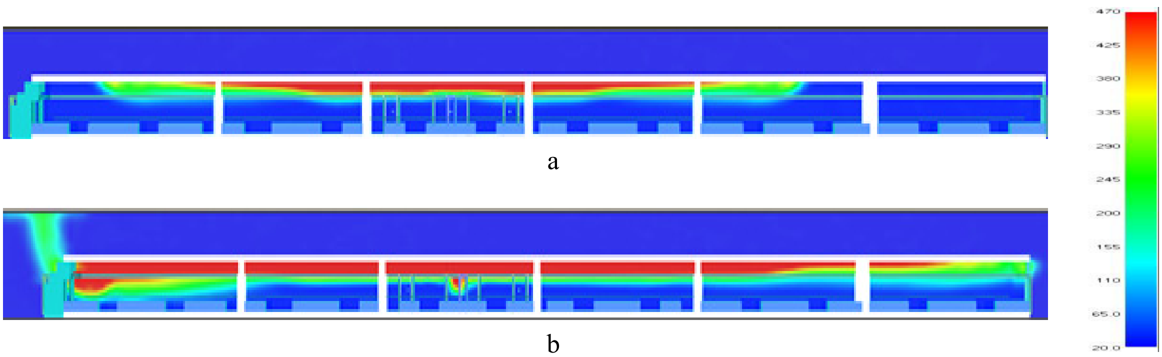

Fig. 8. Temperature distribution in the car: (a) 60s; (b) 120s.

Comparing Fig. 8 and Fig. 9, the distribution of CO2 content and temperature is highly consistent. Temperature of the orange area in Fig.9 is 100℃,and tolerance of skin will decline shapely when the temperature is higher than 95C. At this time, the space of people gathering in the emergency exit is full of high temperature smoke. Whereas,the distribution of temperature in the carriage is as following after 216s when the evacuation ends (the legend in Fig. 9 is the same as in Fig. 2).

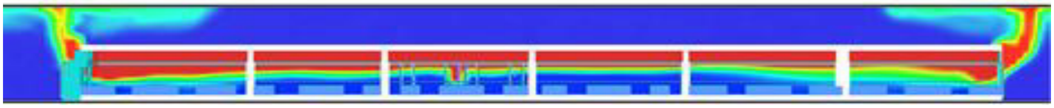

Fig. 9. Temperature distribution in the car at the end of evacuation.

It will cost more time to stay in the high temperature smoke environment in situ evacuation than station evacuation. The smoke temperature in the carriage can be demonstrated higher than 100℃ when evacuation ends in Fig. 9. Under the circumstance of high temperature like this, the possibility of safe evacuation is lower than station evacuation.

The comparison of the efficiency of different evacuation programs was presented in Fig. 10.

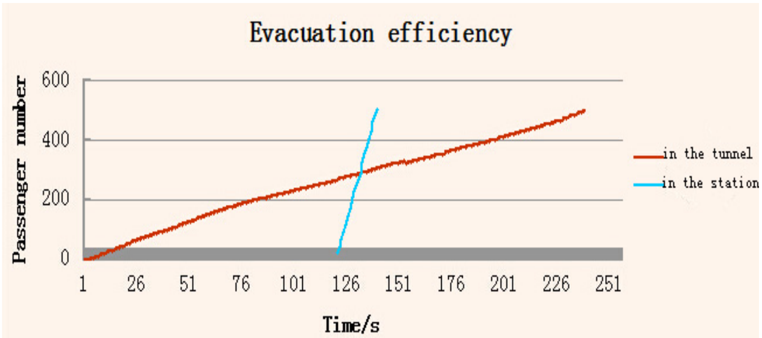

Fig. 10. The comparison chart of evacuation efficiency.

As evacuation in place through the both exits of the train, so the statistics is the average of the two exits. According to Fig. 10, the efficiency of evacuation in the station is much better than the evacuation in the tunnel and its time is short. However, the evacuation program of the train pulling in the station needs a long arrival time, but in the other program an immediate evacuation can be conducted.

5. Conclusions

While subway passes through the middle of tunnel, if it catches fire and can reach station eventually, the evacuation program for subway pulling in the station is superior to that in place. The exposure time of the former under high temperature smoke is less than the latter, thereby the evacuation program for subway pulling in the station has more security.

In this research, the total evacuation time consists of two parts (i.e. reaction and action time). Reaction time is from detecting a fire to opening emergency evacuation route while action time is a period between the first and last person walking out the emergency exit. The above researches show evacuation in place decreases reaction time but increases action time significantly. However, evacuation for subway pulling in the station needs a longer action time but total time is less. In addition, with the increase of tunnel length, reaction time will be continuously extended. Hence, not all tunnel fires are suitable for the evacuation of subway pulling in the station, and the appropriate evacuation program must be determined according to the tunnel length and the location of subway.

In order to evacuate as many people as possible, the best solution is to combine the advantages of two programs that quick reaction of evacuation in place and short action time of evacuation of subway pulling in the station, but the most effective way is to change the setup of the emergency exit. This simulation indicates there is a severe defect in the evacuation of China's subway system that the emergency exits are setting up at the head and the tail of subway. Under the condition of a single fire source, the safe evacuation of all passengers can not be guaranteed, therefore various emergencies (e.g. multi-fire sources caused by arson, terrorist attack and subway losing power due to fires, etc.) can result in catastrophic accidents easily. At present, subway in abroad and some regions of China has adopted the side evacuation platform. Although its cost is high, the efficiency of personal evacuation is much higher than that of the backward port evacuation in an emergency.

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